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**14. ABSTRACT**
This research examined potential ways to optimize meteorological and oceanographic (METOC) analyst training and performance during mine counter measure (MCM) operational tasks. Virtual environments (VEs) and virtual interfaces were used as tools that support comprehension of sedimentation transport data. Novel techniques were developed for the visualization of sedimentation transport data. An interface for the visualization was also developed based on a cognitive task analysis of a sedimentation transport expert. In addition, three experiments were designed to examine the cognitive aspects (spatial cognition and comprehension of oceanographic data) of immersive VEs. The results revealed individual differences in the way people represent objects in space as they navigate in a VE, and these differences have an impact on VE usability. As the level of immersion in the VE increased, scientists required more time and more hints to comprehend remotely sensed oceanographic data. The implications of these results are discussed.

**15. SUBJECT TERMS**
scientific visualization, interface design, spatial cognition, immersive and nonimmersive environments

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FINAL TECHNICAL REPORT

GRANT #: N000140010560

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INSTITUTION: Mississippi State University

GRANT TITLE: Virtual Environments and Virtual Interfaces for Oceanographic and Meteorological Scientific Visualization

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OBJECTIVE:

*Background*
In the 21st century Navy, war fighting objectives include technological superiority, reduced staffing, and an affordable force. Given the requirement of superior performance with fewer personnel, the Navy has a critical need for research that addresses human performance enhancement. The present research investigated how cognitively based design principles enhance human performance in complex technological interactive task environments. Because success in this research requires knowledge of multiple disciplines, a multidisciplinary research team was required. Our collaborative team included researchers trained in computational engineering, computer science, cognitive science and cognitive psychology.

*Project Goals*
The specific goal of this project was to investigate cognitively based virtual environments (VE) and interfaces that optimize meteorological and oceanographic (METOC) analyst training and performance during mine counter measure (MCM) operational tasks. METOC personnel depend on advanced visualization tools to obtain information that will aid their decision making in tactical planning tasks. These visualization systems render copious amounts of data in order to represent complex scientific phenomena. In the present context, the data show historical or forecasted changes in oceanographic conditions over time. In a virtual METOC visualization environment, the analyst was "immersed" in the simulation, which was hypothesized to allow more insight into the dynamic processes of coastal regions coupled with the operational task at hand.

Analysts can interact with a VE via a virtual interface (VI) in order to build an understanding of represented oceanographic conditions. In other words, the analyst uses the virtual interface to focus on information used to build a mental model of the simulated environment, or a "situation model" (Durso & Gronlund, 1999). "Situation model" is a term used to describe a person's understanding of a represented environment (e.g., Doane & Sohn, 2000; Doane, Sohn, McNamara, & Adams, 2000; Sarter & Woods, 1991; Sohn & Doane 2000). In the present context, the analyst uses the situation model of the oceanographic conditions to inform his or her tactical planning decision-making (e.g., determine if cloud cover allows a stealth approach to shore; rate the probability of a sonar contact being a mine based on oceanographic conditions impacting sonar image quality; see Trafton et al., 2000). The goal of the application designer, then, is to provide analysts with interface tools that facilitate the construction of a situation model that will support the highest quality tactical planning decision making. In other words, the virtual interface should enhance human analyst performance.

The specific focus of the project was on the scientific visualization of oceanographic data used in the study of sedimentation transport. The study of sedimentation transport is important for the Navy MCM community, in instances where historical records of past mine contacts must be examined. For example, MCM personnel may need to determine if sediment has concealed previously detected mines since the last time they were encountered. The objective of this project was to use principles of human-computer interaction and applied cognitive science to address human information-processing and system design issues relevant for scientific visualization tasks, such as the study of sedimentation transport. This objective included several subgoals. One set of subgoals involved the design of the visualizations and the interface for that visualization. Another set of subgoals involved the nature of the virtual environment used to display the scientific visualizations.

*Design of the Visualization*
Many of the problems we face today involve complex relationships between variables representing interrelated processes. It is computationally expensive both to model these processes and to analyze and understand the huge amounts of data generated. Often the best way to analyze these relationships is visually, with some form of graphic representation. In the past, it was sufficient to display any representation that the computer could render, forcing as much information as possible into one image. We have reached a computational threshold where we can often display more information than is useful, and so now we are concerned with the perceptual issues of combining colors, primitives (i.e., graphical building blocks), and textures such that we can gain the greatest understanding of what is rendered.

Producing meaningful visualizations now means maximizing how well the information they convey is perceived. What types of visual techniques will best show information about complex relationships between variables, especially when used in combination with other techniques? Many times there is no single solution, but hybrid solutions, such as using one technique to "browse" data on a macro scale to identify areas of interest, then using another method to show detailed information within a smaller context ("drill down"), often provide the best answer. Within this context, we have developed a new method for conveying information about size-fractionated sedimentation concentrations (browsing) within a larger visualization of related variables. Accurate modeling of environmental processes such as sedimentation (i.e. the settling of clay, silt, and sand to the bottom of a body of water) and aerosol distributions (e.g., precipitation, dust, pollutants, or biochemical toxins) is better achieved if the concentrations are more accurately differentiated by particle size. Computing and rendering information related to multiple scalar fields, where before there was only a single field, is a significant challenge for the area of visualization design.

One goal of our visualization design has been to enable analysts at Stennis NRL to study complex littoral region processes, such as how a Navy diver's visibility might be affected by changes in weather and the surrounding underwater environment, including sedimentation (Keen, Vickery, Flynn, Stavn, & McBride, 2001; Vickery et al., 2002a). Additionally, Navy MCM operations can use the information on erosion and deposition of sediment to understand burial characteristics of mines in specific underwater regions.

*Design of the Interface*
In addition to the concerns about designing a visual representation of the data, analysts must be able to interact with the representation effectively once it is completed. In order to design a usable interface for such a visualization, the analyst's information requirements must be understood and incorporated into the interface. The user with whom we were most concerned was an expert in sedimentation transport, Dr. Tim Keen. Dr. Keen has developed a computational model of sedimentation transport that can calculate the characteristics of the ocean bottom given a set of remotely sensed data as input.

Dr. Keen's tasks with his model are two-fold. First, he must diagnose problems in the data sets that his model generates based on his knowledge of oceanographic processes. Problems that he finds may be caused by errors in his model's calculations or by a bad set of input values. Using traditional methods of analysis, finding and diagnosing such problems in a data set is a time-consuming process.

The second task Dr. Keen must accomplish with his model is understanding the state of the ocean from the model's output. That is, he must integrate the various pieces of data mentally in order to make predictions about the future states of the ocean.

Cognitive task analysis is one method that has been used to understand user information requirements for the design of interfaces (e.g., Endsley, 1993; Schraagen, Chipman, & Shalin, 2000). In our cognitive task analysis, we focused on gaining an understanding of how our SME, Dr. Keen, uses the information he has about an oceanographic environment to diagnose problems with his model of sedimentation transport. Our first goal in the analysis was to determine the relationship between different pieces of information, according to our SME. Knowing the relationships between aspects of the data gave us a better understanding of when certain information would be important for Dr. Keen to be able to access quickly. Our second goal was to develop a process diagram that described the steps Dr. Keen took to diagnose problems with his model. The process diagram would also help us design an interface that could present useful information to Dr. Keen at the right times and in the right way.

*Immersive Versus Nonimmersive Environments*
With the increase in VE technology, some researchers have hypothesized that a heightened sense of "presence" in a VE would lead to better understanding of information presented in the VE (e.g., Slater & Wilbur, 1997). Presence can be thought of as the sense that the virtual world is a real environment that the user is actually standing in and interacting with. When an environment is thought to offer a high sense of presence, it is referred to as an "immersive" environment. The impact of immersion or presence on a user's understanding of information is also important to understand. Immersive systems are often very expensive to purchase and to maintain. If a less immersive environment can support the information-processing requirements needed for the scientific visualization of oceanographic data as well as an immersive environment, then the Navy should consider using the less expensive alternative. The impact of immersion on user understanding of information was examined in another experiment conducted for this project.

*Spatial Cognition in Virtual Environments*
There are many differences between the real world and even the most high-fidelity virtual environment. Some of the most documented differences involve spatial cognition (e.g., Cutting, 1997; Loomis, Blaschovich, & Beall, 1999). Because visualization has an inherent spatial component, it is important to understand how spatial cognition in a VE differs from the real world. Such differences may be important for the design of appropriate visualizations and interfaces in VEs.

Numerous theories have been developed about how people keep track of the elements of their environments in the real world. Two of the major theories in the literature are the configural theory and the egocentric theory of spatial cognition. The configural theory states that people keep track of objects in space around them by storing information about the object-to-object relationships they encounter (e.g., Sholl & Nolin, 1997). Such information leads to the formation of "cognitive maps," that can be considered mental representations that have the properties of models of an environment. Cognitive maps are believed to be allocentric, or independent of any specific orientation taken by the person in the environment. The egocentric theory states that people keep track of the relationships between objects in an environment and their own body's position in the environment (e.g., Wang & Spelke, 2000). The egocentric theory suggests that object locations are represented in transient "snapshots." These snapshots can be recalled when a person is not in an environment, but they can only be recalled from the particular orientation in which they were "taken."

Given these two theories and the previous research on spatial cognition performed in the real world, we conducted a set of studies to determine what representations were used when performing spatial tasks in a VE. Our investigation led to a study of the strategies people can use in order to effectively navigate in VEs, and the results from that study may guide future work on designing navigation tools for VE interfaces.

Taken together, the results of our efforts produced valuable information about the design of scientific visualizations and interfaces for the visualizations. Although our objectives focused on scientific visualization of oceanographic data, much of our work should generalize to other areas of scientific visualization.

## APPROACH:

For this research program, our goals included designing visualizations, designing the interface for the visualization, studying the nature of spatial cognition in the virtual environment used to display the scientific visualizations, as well as studying the impact of immersion on understanding scientific data presented in a VE. Our applied emphasis included visits to Pensacola MCM facilities to talk with METOC analysts (e.g., LTjg Jay Jones at NAVTRAMETOCFAC), and visits to NAVO and NRL at Stennis to talk with METOC analysts there (e.g., Dr. Timothy Keen and Steve Lingsch at NAVO Stennis). The goal of these discussions was to determine the content and nature of the information these analysts use during their decision-making process. The results from these discussions and formal task analyses, coupled with our theoretical findings, enabled us to develop cognitively based design principles for MCM METOC VEs and VIs. The specific details of the approach we used for each of our goals will be discussed in turn.

*Design of the Visualization*
The approach for the visualization portion of this project was to develop new visualization algorithms for complex physical problems and to compare them with other state-of-the-art techniques in terms of rendering speed and user-

perceived effectiveness. User studies comparing the new visualizations to the state-of-the-art techniques were developed with a focus on the interactivity of the visualizations, as well as on the effectiveness of the visualization as a means of presenting information to the users. Further information on the visualization can be found online at http://WWW.ERC.MsState.Edu/~rvickery/.

*Design of the Interface*

For the design of the interface, a cognitive task analysis was performed to help understand the information requirements and procedures for studying sedimentation transport in the littoral ocean environment. The cognitive task analysis began with several interviews with our SME. Following the initial interviews, we used several techniques to gather more information about how the SME used his model to analyze sedimentation transport data. The first technique was a hierarchical card-sorting task. In this task, the SME was given many index cards, each having the name of one variable written on it. The SME was asked to group the index cards by greatest similarity and to label the resulting groups. The SME then combined the groups based on greatest similarity and labeled the new, larger groups. This process continued until all the index cards were in one large group labeled "variables." The result of this grouping was a hierarchical sorting of the variables that could be used to represent the SME's representation of the sedimentation transport domain (Doane, Pellegrino, & Klatzky, 1990). Figure 1 shows the knowledge representation diagram that resulted from this task.

After examining the hierarchy of variables, we watched the SME perform his diagnostic tasks. The notes taken from that process were used to build an initial process diagram showing the steps the SME used to examine the oceanographic environment. This diagram was refined through interviews and more observations of the SME performing his tasks. The purpose of this process diagram was to inform our interface design by describing when and how information was used during the task.

Figure 2 shows the process diagram for the portions of the SME tasks on which we focused. Specifically, it shows the process of searching for and diagnosing anomalous points in an oceanographic data set. Based on the cognitive task analysis, we designed storyboards for an interface and refined our ideas by using rapid prototyping tools and further discussions with the SME. The interface was later tested, and the results of the tests are discussed in the "Immersive Versus Nonimmersive Environments" sections of this report.

*Immersion Versus Nonimmersive Environments*

Once the interface design was finalized, it was implemented in two systems. The systems used were a flat-screen computer and a four-walled Cavernous Automatic Virtual Environment (CAVE). Figure 3 shows the flat-screen version of the interface and the visualization, whereas Figure 4 shows the CAVE version of the interface and the visualization. These systems were chosen because of the relative amount of "immersion" inherent in their use. That is, the flat-screen computer is not generally considered as immersive as a CAVE (Cruz-Neira, 1998). By implementing the interface in two systems that differed in levels of immersion, we could test the impact of immersion on the scientist comprehension of the visualization.

When the interfaces were completely implemented, our SME served as a subject in an experiment investigating the impact of level of immersion on scientific data comprehension. Before the experimental tasks were given to the SME, he was trained to use both interfaces. Training consisted of having him perform simple tasks that required the use of each part of the interface in turn. For example, he was first asked to navigate to a specific point in the ocean environment. This meant that he had to use the navigation function of the interface, such as manipulating the wand in the CAVE or using the mouse to press the movement icons in the flat-screen interface. Once the SME was trained on both interfaces, the experimental tasks began.

The tasks used in the experiment were designed to test the SME's comprehension of the data being visualized. For each task, a certain point in an ocean environment was manipulated to cause an anomaly in the data. For example, the SME might be presented with an environment in which the ocean bottom was composed of fine silt. The anomalous point might have a very coarse mud in place of the silt, changing the properties of the currents, sediment entrainment, etc. The SME would first have to find the anomalous point in the environment, then diagnose what caused the anomaly. In the previous example, that would involve determining that the sediment coarseness had been manipulated for the anomalous point. If the SME felt he could not make progress on any part of a task, he could request hints from the experimenter. While he used each interface, we recorded the amount of time it took our SME to use commands, find anomalous points, and diagnose problems. These reaction times were compared across the systems, as were the number of hints required to solve the problems accurately.

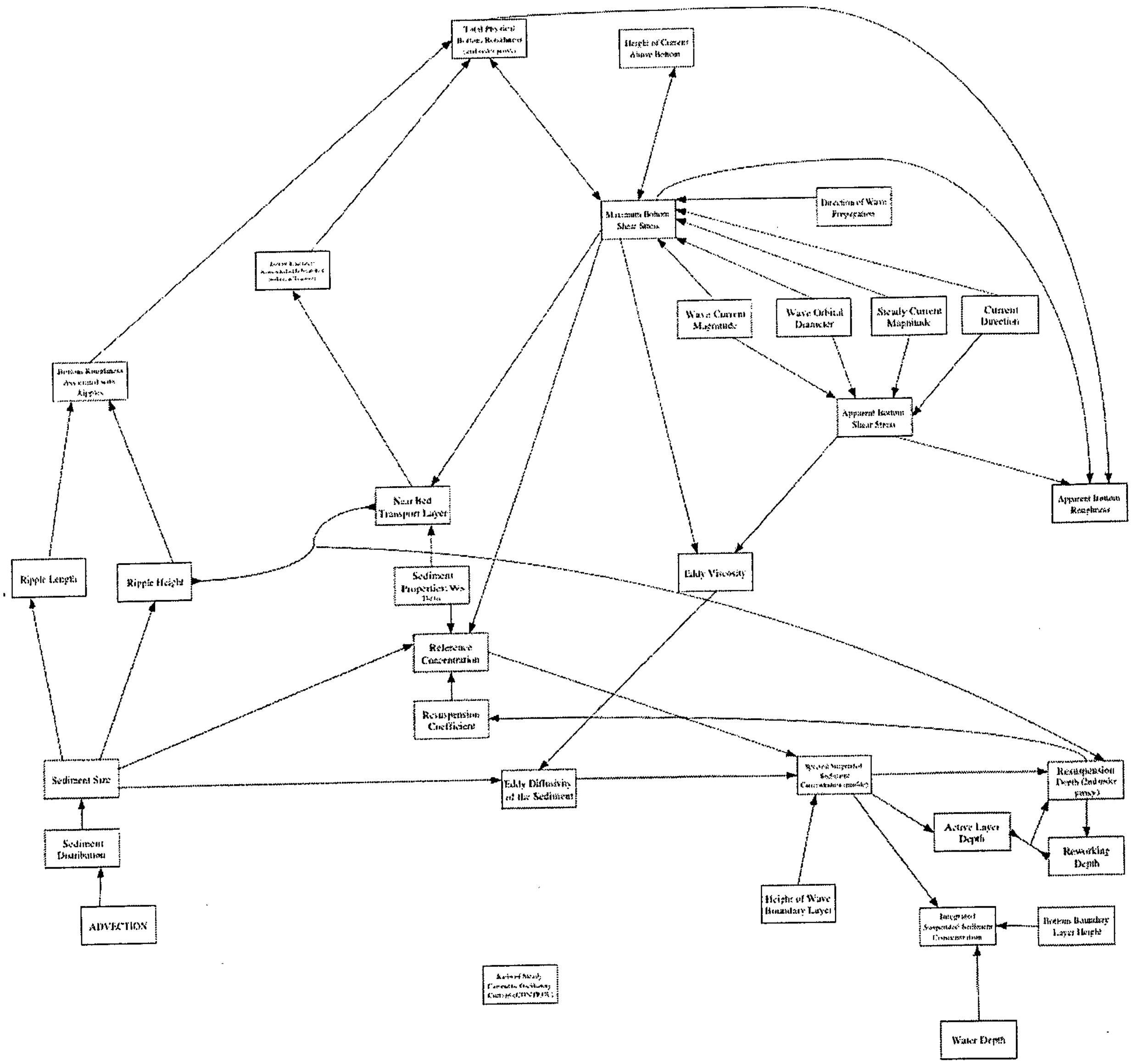
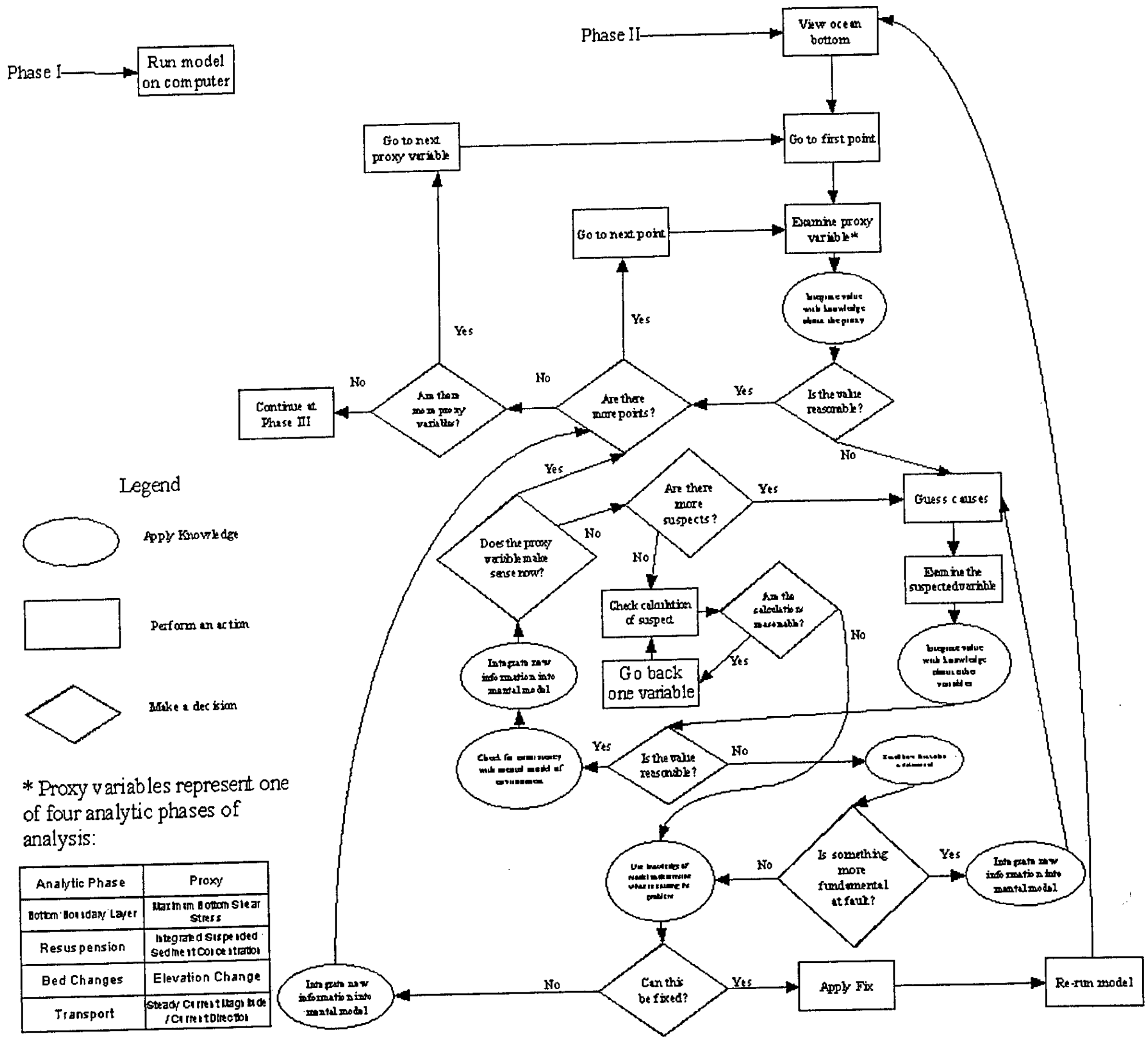



*Figure 1.* Representation of SME's conceptual structure of the variables involved in sedimentation transport.

*Spatial Cognition in Virtual Environments*

Real-world studies of spatial cognition have focused on understanding the underlying mental representations used by individuals while navigating through space (e.g., Shelton & McNamara, 1997; Sholl & Bartels, 2002). In order to examine the ways that people navigate in VEs, our research adapted a research paradigm used for studying spatial cognition in the real world (see Wang & Spelke, 2000). The paradigm we used contrasted the configural and egocentric theories of spatial cognition. These theories predict different effects of being disoriented in an environment. According to the configural theory, a person represents the configuration of an environment through object-to-object relationships instead of through self-to-object relationships. Thus, the configural theory suggests that people should still be able to access the relative positions of objects in an environment, even after losing their sense of orientation.

By contrast, according to the egocentric theory, a person must access self-to-object relationships in order to recall the positions of objects in space. Thus, the egocentric theory suggests that people should lose their ability to access the relative positions of objects following disorientation. If this theory is correct, then when information about self-position is lost, accessing self-to-object relations should become difficult.




| Analytic Phase | Proxy |
|---|---|
| Bottom Boundary Layer | Maximum Bottom Shear Stress |
| Resuspension | Integrated Suspended Sediment Concentration |
| Bed Changes | Elevation Change |
| Transport | Steady Current Magnitude / Current Direction |

*Figure 2.* Process diagram for SME's analysis of anomalous points in oceanographic data.

In order to determine which type of representation people are using in the VE, we had subjects learn the locations of six objects in a virtual world. Figure 5 shows an example of a subject studying the locations of objects in the CAVE. Once the subjects had learned the locations, they were asked to indicate the object locations when the objects were occluded from view. This was first done while the subjects were oriented in the environment, and later while they were disoriented wearing a blindfold. Figure 6 shows an example of a blindfolded subject pointing to objects using the wand. From subject responses, a configuration error was calculated. Configuration error was thought to describe the tendency for a subject to recall the object-to-object relationships accurately. The difference in configuration error between oriented and disoriented phases indicated the type of spatial representation the subject was using. If the subjects showed an increase in configuration error following disorientation, this indicated the subject was using an egocentric representation. If the subject showed no increase in configuration error, this indicated the subject was using a configural representation. Findings from our initial study showed that there are systematic individual differences in the types of representations used by individuals when they navigate in a VE. Further, the subjects were shown to use strategies to improve their performance on spatial tasks. Our investigation of spatial cognition in VEs later expanded into a study of the types of strategies subjects could use to perform spatial tasks in a VE. We specifically examined how strategies used by subjects were affected by the type of representation they were using.

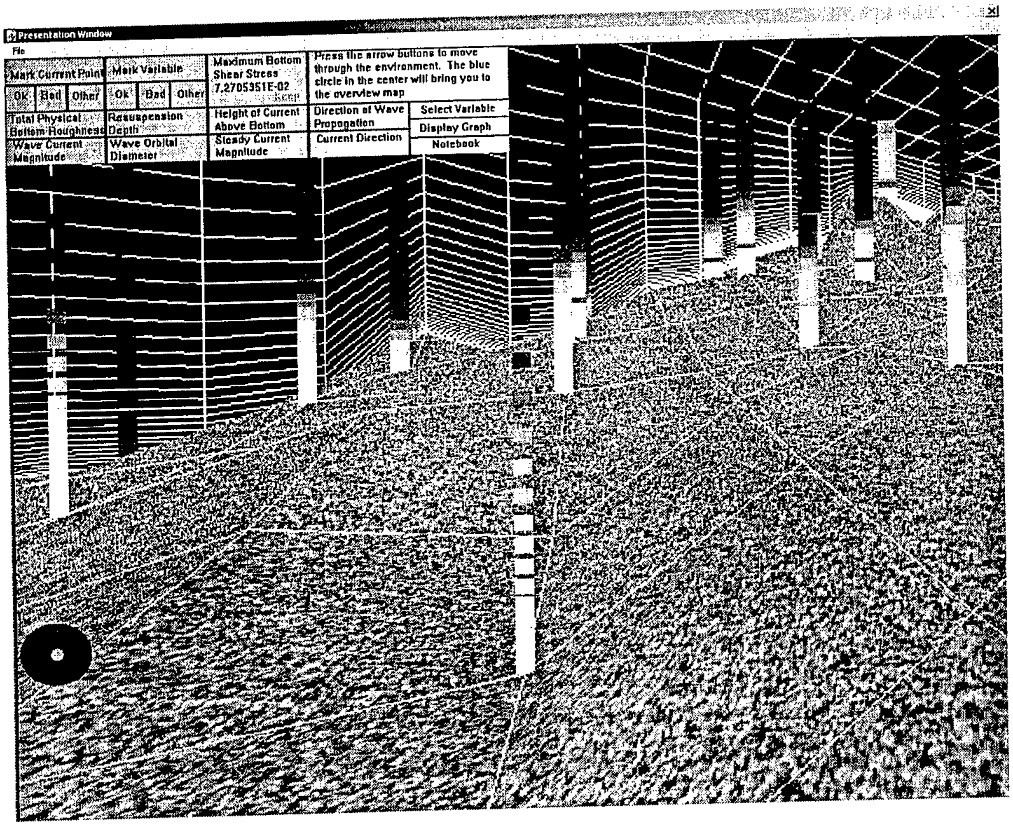



*Figure 3.* Screenshot of the flat-screen version of the interface and the visualization.

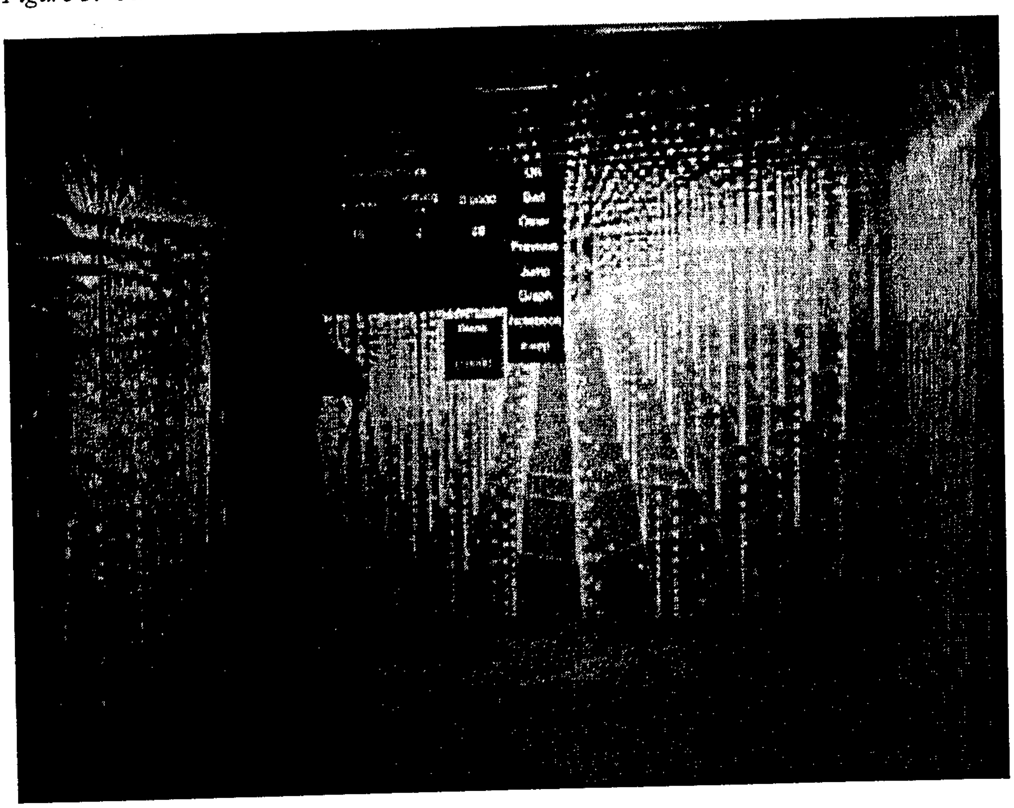


*Figure 4.* Screenshot of the immersive CAVE version of the interface and visualization.

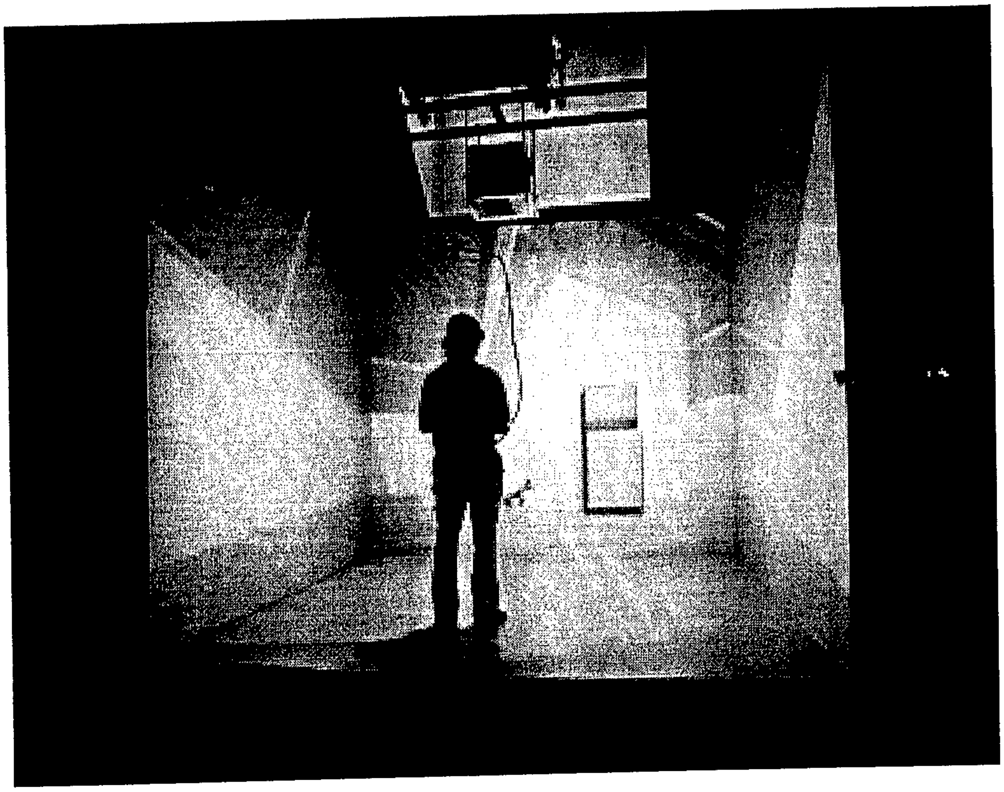


*Figure 5.* Example of a subject studying the locations of objects in the spatial cognition experiment.

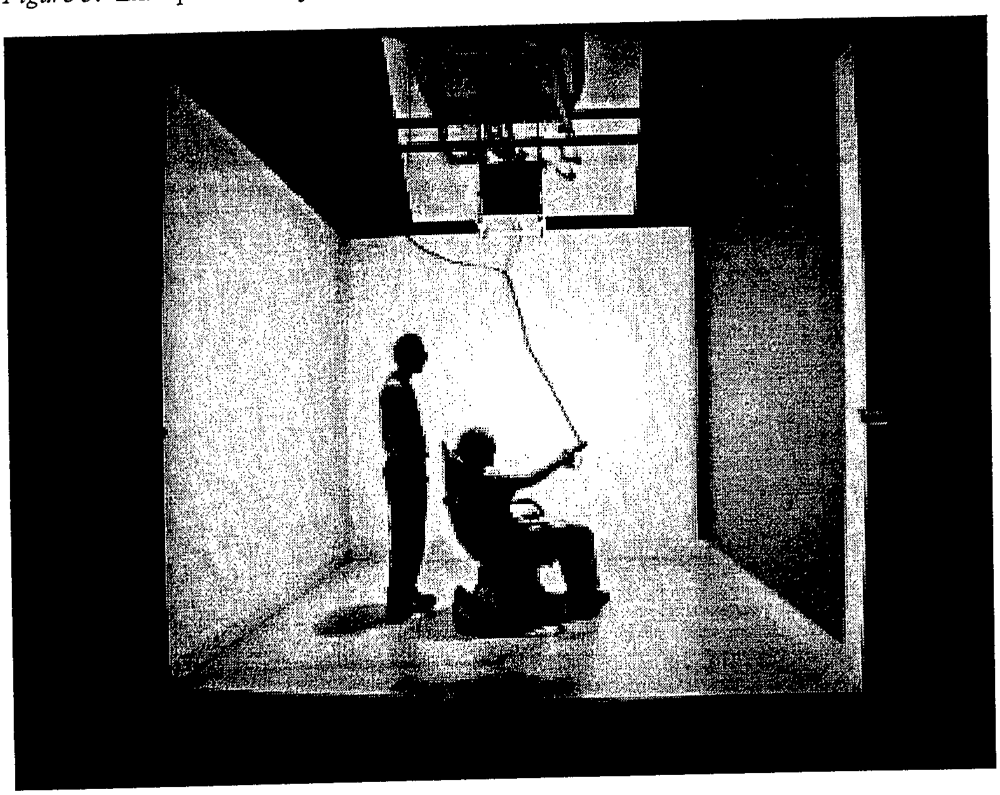


*Figure 6.* Example of a blindfolded subject indicating the locations of objects in the spatial cognition experiment.

ACCOMPLISHMENTS (throughout award period):

*Design of the Visualization*
We started by implementing a basic system to visualize the available scalar and vector variables produced by the oceanographic sedimentation model. In addition, we addressed some of the usability issues relating to the system's use in Mississippi State University's VE (Keen et al., 2001; Vickery et al., 2001). We then added a new volume visualization method that allows multiple related scalar variables to be viewed with other relevant data (Vickery et al., 2002a). This method suffered from two major shortcomings: Sedimentation particles of vastly different sizes were displayed as the same size, and there were too many colors to distinguish distinctly between the different scalar fields. Therefore, the algorithm was enhanced to view multiple related scalars more effectively by incorporating a better range of colors and sizes (Vickery et al., 2002b). In the enhanced version, color is used to separate up to 20 related scalars or "bins" (in this case differentiated by grain size) into 4 general categories (representing clay, silt, sand, and gravel). Within the categories, varying size glyphs (i.e, visualization constructs used to represent scalar values) show the magnitudes for each bin. Smaller glyphs show magnitudes for smaller grain size bins, and larger glyphs for larger grain size bins. This combination of color and size provides two levels of detail to help the analyst determine the types of sediment present in the water. The addition of logarithmic scaling to the computation for the number of glyphs and how they are allocated to different regions within the VE was another major enhancement.

To determine if our implemented visualization method was effective for viewing large datasets, we chose two criteria: interactivity in the VE and effectiveness as an information visualization method. Because our implementation renders the information as particles, we compared the interactive performance of our method with two of the most common methods for displaying particles in the VE (Vickery et al., 2003a). This study helped us determine how parameters needed to be set to maximize the interactivity of our implementation. We were able to show that our method was at least as interactive as the other two in the worst case, and up to 44 times more interactive in the best case.

We have just completed a pilot study on the effectiveness of our method as an information visualization technique for browsing large datasets. The information obtained is being used to design a formal user study that will focus on how well the related scalar values are represented as texture mapped glyphs, and also how well the method compares with another state-of-the-art visualization methods (Vickery et al., 2003b).

We have also enhanced an existing library of VE interface programming tools, called widgets, that can be used to prototype both a developer's graphical interface, as well as a custom interface to support specialized user studies (Brou & Doane, 2003). One particularly useful widget was created as an aid to help analysts understand the effect of logarithmic scaling on the visualization of scalar variables with a range of values too large to represent linearly. This interactive widget maps scalar values to a color-mapped legend, such that the analyst can see the exact value of the scalar field represented by a specific color on the logarithmic scale (Noble et al., 2003).

*Design of the Interface*
In the past, sedimentation transport analysis involved examining printouts of 2-D slices of the ocean in an area. These slices showed numerical values for one variable at regular intervals in an ocean region. Because the analysis of sedimentation transport required a mental model of the status of many variables in an area and how the variables interacted, the traditional method of analysis was an extremely demanding task.

In our approach, we first completed a cognitive task analysis for an oceanographic sedimentation transport expert. From this analysis, we generated a knowledge representation diagram and a process diagram on which an interface design was based. We predicted that the time required for sedimentation transport analysis of a littoral region would be significantly decreased by using a VE with the interface designed from our task analysis, because the VE and interface would facilitate the effective building of a qualitative mental model of the littoral region (Trafton et al., 2000).

Our interface design was implemented in both a nonimmersive and an immersive environment. Our SME described our interface as "an order of magnitude better" than the traditionally used system for sedimentation transport data analysis. Because the interface was implemented in multiple types of systems, we were able to use it in a study of the impact of immersion on the comprehension of scientific visualizations. The details of that study are reported in the "Immersive Versus Nonimmersive Environments" sections of this report.

*Immersive Versus Nonimmersive Environments*

The results of the experiment examining the impact of immersion on comprehension of scientific visualizations showed that immersion did not enhance comprehension of scientific visualizations, as the SME was able to complete all tasks in both the immersive and the nonimmersive environments. Further, the SME took longer to complete the tasks and required more hints about the tasks when he used the immersive environment to study the visualizations. Figure 7 shows the mean amount of time needed by the SME to locate anomalous points in the immersive and nonimmersive environments. Figure 8 shows the mean number of hints needed for solving tasks in the two environments. The SME reported that both the immersive and the nonimmersive environments were superior to the traditional methods of data analysis. The results of this study are currently being prepared for publication.

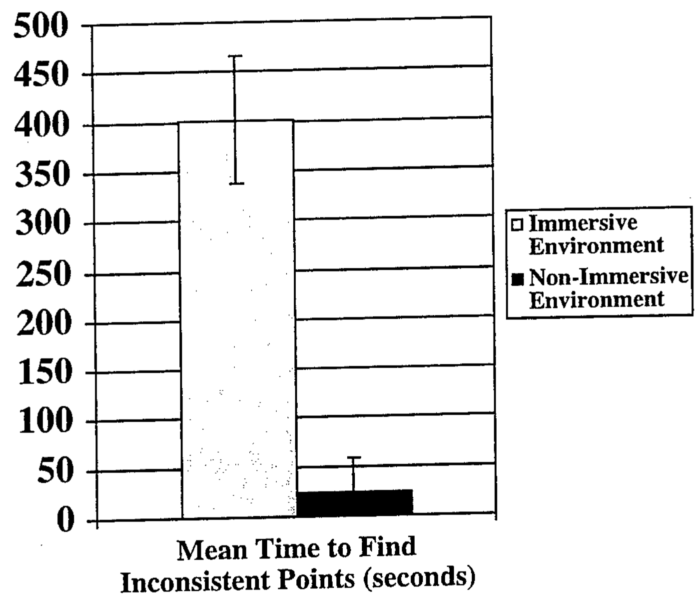



*Figure 7.* Mean time required (in seconds) for the SME to locate anomalous points in the oceanographic data using the immersive and nonimmersive environments.

*Spatial Cognition in Virtual Environments*

We completed two experiments investigating spatial cognition during this project. The first experiment showed that there are individual differences in the representations that people use to navigate in VEs. That is, about 1/3 of the subjects we tested formed configural representations of the VE, whereas 2/3 formed egocentric representations. Further, the subjects who formed egocentric representations were able to employ a strategy of assuming a familiar orientation (i.e., recalling an egocentric snapshot of a previously viewed orientation) in order to perform the object localization task effectively following disorientation. Figure 9 shows an example of a subject who is initially facing the plant in our experimental environment before being disoriented. Following disorientation, the subject might assume a familiar or an unfamiliar orientation. These two possibilities are illustrated on the right side of Figure 9. On the top right, the subject points as if facing a familiar orientation (i.e., towards the plant); on the bottom right, the subject points as if facing an unfamiliar orientation (i.e., towards the television). Subjects using an egocentric representation chose orientations that were more familiar than subjects who used a configural representation. This familiar orientation strategy facilitated their recall of object locations, even though their sense of orientation in the environment had been lost. Figure 10 shows the mean distance from a familiar orientation chosen by configural and egocentric subjects. Our second experiment showed that subjects who initially used a familiar orientation strategy could not perform the task effectively if they were not allowed to use that strategy. The experiments on spatial cognition have led to three conference papers and one paper under review for publication in *Spatial Cognition and Computation*.

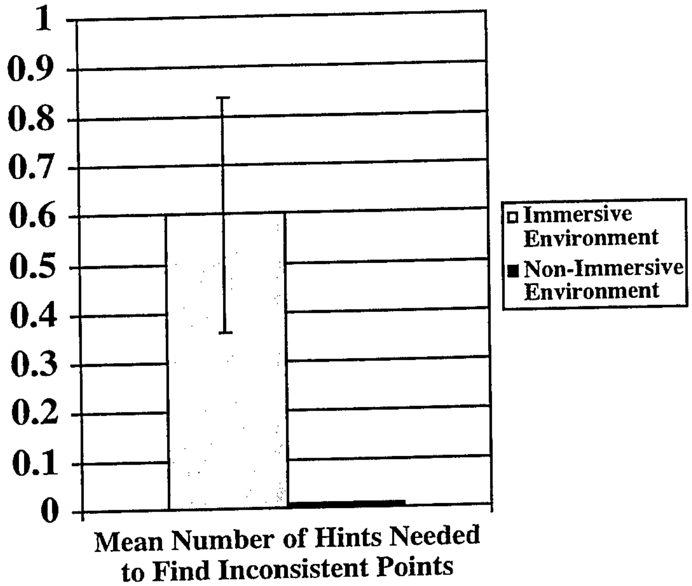



*Figure 8.* Mean number of hints needed for the SME to complete tasks accurately in the immersive and nonimmersive environments. In each case, the SME required hints about the location of anomalous points in the oceanographic visualization.

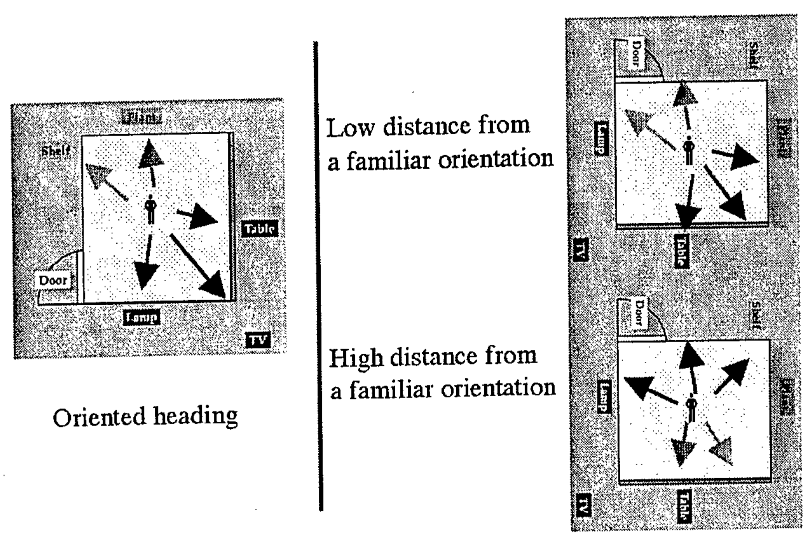



*Figure 9.* Diagram of a subject selecting a high or low distance from a familiar orientation. On the left, a subject may initially have a heading in which the plant is directly in front of him or her. If, after disorientation, the subject assumes the plant is still in front of him or her (i.e., top right figure), that subject is described as having a low distance from a familiar orientation. If, after disorientation, the subject assumes a novel orientation, in which the plant is not in front of him or her (i.e., bottom right figure), that subject is described as having a high distance from a familiar orientation.

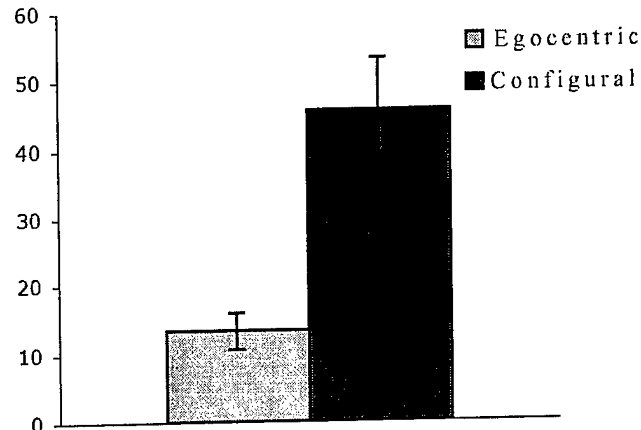



*Figure 10.* Mean distance from a familiar orientation selected by subjects as a function of mental representation in the spatial cognition experiment.

## CONCLUSIONS:

*Design of the Visualization*
Understanding complex physical processes in a VE is a difficult problem with no single solution. Effective visualizations for VEs are designed by understanding the context of the problem and the relationships between variables to determine the information desired. The best visualizations are often combinations of existing methods that display the information based on the amount of detail required. Hence, some techniques work best to browse data over a large area. These techniques can be used to identify specific grid locations where higher detail techniques can be used to obtain more specific information.

In this project, we discovered that the texture mapping algorithm was most effective for browsing large areas to understand global changes in sediment concentration at a glance. More detailed techniques were used to show the breakdown of related scalar variables for specific grid locations. It is this combination of techniques used in the proper context that has provided the most complete information for the analyst.

*Design of the Interface*
Using a cognitive theory-based approach to the design of the virtual interface, we successfully built a tool that facilitates a scientist's ability to perform oceanographic data analysis. Our interface was designed to lessen the mental workload of the user, giving memory support tools and shortcuts based on the information requirements of the scientific visualization tasks. Our SME found the use of our interface to be superior to the traditional methods of oceanographic data analysis.

*Immersive Versus Nonimmersive Environments*
In our experiment on the impact of immersion on the comprehension of scientific visualizations, we recorded reaction times to complete tasks in an immersive and a nonimmersive version of our interface. An analysis of those reaction times showed that the SME required significantly more time and more hints to complete the tasks in the immersive CAVE environment. Both of these findings can be explained by the fact that the SME "got lost" in the visualization in the immersive condition. That is, with so many data points in view at one time, the SME had difficulty spotting the areas of interest in the visualization (see Figure 7). This finding is important for at least two reasons. First, we failed to support the idea that immersion leads to better comprehension of scientific data. Second, the findings suggest that more research is required to understand when an immersive VE can be superior to a nonimmersive environment.

*Spatial Cognition in Virtual Environments*
The results of our research in spatial cognition have shown there are individual differences in the way people represent objects in space as they navigate in a VE. That is, about one-third of our subjects appeared to use a configural representation, whereas two-thirds of our subjects showed evidence of using an egocentric representation. Further, the people using an egocentric representation were able to use a specific strategy to complete our spatial task following disorientation. This strategy consisted of assuming a familiar orientation in the environment and recalling an orientation-specific snapshot in order to respond to object location queries. Future research in interface design for VE navigation might be able to take advantage of our findings. Because subjects can generate appropriate strategies that optimize the use of their mental representations, an interface design might incorporate elements that facilitate the use of such strategies.

## SIGNIFICANCE:

*Design of the Visualization*
Accurate modeling of environmental processes such as sedimentation (i.e., clay, silt, and sand) and aerosol distributions (e.g., precipitation, dust, pollutants, or biochemical toxins) is better achieved if the concentrations are more accurately differentiated by particle size. Computing and rendering information relating to multiple scalar fields rather than just a single field as before is a significant challenge for this area, especially when the desired result is to understand related variables underlying complex physical processes.

The benefits of our research included an enhanced knowledge of emerging computer technologies that may become prevalent in the future. Another benefit is an improved understanding of the specific components of VR technology that would be most helpful in information visualization. Thus, future development can focus on using specific mechanisms of VEs to improve analysis. The final result would be better visualizations for scientific inquiry.

*Design of the Interface*
The approach we took to design our interface was to use principles from human-computer interaction and cognitive science. Our interface was shown to facilitate a scientist's ability to perform data analysis using scientific visualizations. This finding supports the idea that the use of cognitive theories as design principles is a viable and useful approach to the design of interfaces. Further, our task analysis produced a knowledge representation diagram and a process diagram that are still being used to guide future work on scientific visualizations for oceanographic data analysis. That is, these documents will enhance interface designs beyond the scope of this project.

*Immersive Versus Nonimmersive Environments*
The finding that immersion does not necessarily enhance comprehension of remotely sensed oceanographic data is an important finding for the Navy. If immersive displays do not provide further information to scientists, then visualizations can be developed on less expensive, nonimmersive systems. This also implies that future work in the development of visualizations can focus on optimizing the presentation of information in nonimmersive formats.

Alternatively, future research can investigate the applications for which immersive displays would be more useful. One possibility is that immersive displays would be better suited to scientific visualizations in which an analyst had to view a changing environment. In our studies, the analyst could make inferences about the ocean based on single time-steps. When the task requires the viewing of multiple time-steps, an advantage for immersion may appear.

*Spatial Cognition in Virtual Environments*
Individual differences in spatial representations used to navigate in virtual environments must be taken into account when designing any system that requires navigation. This is particularly true when the designer needs to make tools for navigation available to the users. Future research needs to investigate how designers can fully account for individual differences in spatial cognition in the design of virtual interfaces. It is likely that different sets of tools will better facilitate effective navigation for users with each type of spatial representation.

Another issue addressed by this research is the use of VEs in training. As VE technology has increased, there has been a push to use virtual worlds as training environments. The benefits of using VEs in this way seem numerous (e.g., Loomis et al., 1999). For example, training a firefighter in a virtual building is much safer than training one in a real burning building. These potential benefits will not mean much, however, if the training in a VE does not transfer to the real world. Our findings indicate that many subjects used strategies in a VE to enhance their ability to perform object localization. More research on how these strategies are applied in the real world is needed to enhance the design of VE navigation tools. Alternatively, reliance on VE navigation tools that are not available in the real world may lead to performance during training that is unachievable in the real world. These possibilities must be studied more carefully and weighed into the design of VEs used for training in any real-world task.

PATENT INFORMATION: N/A

AWARD INFORMATION:

Randy Brou: Mississippi State University Psychology Department Annual Research Forum, Ph.D.-level research award for "Effects of Disorientation on Human Spatial Cognition"

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